

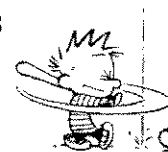


Physics and Acoustics of Baseball & Softball Bats

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Should Metal Baseball Bats Be Banned Because They are Inherently Dangerous?

This article about metal bats and safety is limited to a discussion of adult baseball bats that are currently required to pass the NCAA and NFHS performance standard which effectively, though indirectly, limits the maximum speed that a metal bat can hit a baseball. This discussion does not pertain to metal adult baseball bats manufactured prior to 1999 since those bats are not currently legal for play. This discussion also does not pertain to the smaller diameter youth bats used for Little League which are only indirectly regulated through the BPF 1.15 standard. Adherence to the BPF 1.15 standard for youth bats is currently optional (according to the latest Little League regulations, the requirement that every bat from every manufacturer must pass the BPF standard doesn't actually go into effect until 2009). Finally, this discussion does not pertain to the performance of Senior League large barrel youth baseball bats because these bats are not currently subject to any performance standards at all, though youth baseball associations and researchers are investigating validity of extending the NCAA BESR and MOI standards to these shorter and lighter youth bats.

The debate over whether metal baseball bats should be banned from youth sports because of concerns of player safety has been going on for almost 20 years, though it has gained national attention recently. In the Fall of 2002 the Massachusetts Interscholastic Athletic Association considered banning the use of aluminum bats in high school tournament play for 2003 and for all high school games in 2004, though they ended up not passing the ban. In 2006, after a high school pitcher was severely injured by a hit ball, the state of Montana considered banning bats - but ended up rejecting the ban. Also in 2006 the North Dakota high school athletic association passed a ban on metal bats (it went into effect in the Spring of 2007) for high school baseball citing as reasons: (i) the problems of aluminum bat durability in colder weather and the cost of replacing dented metal bats every year, (ii) a desire to restore the integrity of the game of baseball as played with wood (in terms of batting averages, pitching, and base running), (iii) a desire to improve the development of pitchers and batters by returning to wood, as well as some concerns about the potential safety of pitchers and infielders. In March 2007 the New York City Council passed legislation banning metal bats for high school play, claiming a "mountain of evidence" showing that metal bats hit balls at excessively dangerous speeds and pose a significant safety risk to pitchers and infielders. The NY City mayor vetoed the ban on the grounds that science didn't back up the claims, but the council had enough votes to override the Mayor's veto and the ban is set to take effect in September 2007. State legislatures in New York and New Jersey are currently considering legislation to ban metal bats, so the issue is bound to be in the news for some time to come.

The typical arguments in favor of banning metal bats, arguments that metal bats present a dangerous and intolerable safety risk, usually rely on two assumptions:

1. **Assumption #1:** Baseballs hit by players swinging metal bats travel at extremely high speeds, well in excess of the speeds that could be achieved if the same player were swinging a wood bat. Typical numbers most often quoted are that wood bats hit balls with maximum speeds of 93-

mph while metal bats hit balls with speeds of 100-123 mph.

2. **Assumption #2: Pitchers do not have enough time to react to line drives from metal bats, but would have enough time to react from a line drive from a wood bat.** Typical numbers quoted are that pitchers need 0.4s to react to a hit ball, while balls travelling faster than 94-mph get to the pitcher in less than 0.3s.

In this article I want to explore these assumptions from an impartial scientific viewpoint in an attempt to determine whether or not these two assumptions are valid. In order to determine whether or not metal bats pose an unacceptable safety risk in the sport of baseball, we need to answer the following questions:

1. How fast can a ball be hit using a wood bat?
2. How much faster can a ball be hit with a metal bat compared to wood?
3. How quickly would a ball hit by a wood or metal bat arrive at the pitcher?
4. How much time does a pitcher need to safely react to a batted ball?
5. How does the speed of the ball affect the severity of a ball-impact injury?

How fast can a wood baseball bat hit a baseball?

In a memorandum dated December 4, 1998, the NCAA Baseball Rules Committee stated that:^[1]

"Studies conducted on the Baum Hitting Machine, which all experts acknowledge to be the most state-of-the-art testing machine available, show that traditional wood bats when swung at 70 miles per hour (mph) at a ball moving at 70 mph will produce an exit velocity of approximately 93 mph or less."

Based on these test results, the NCAA initially considered a 93-mph performance standard for bats. However, when the NCAA finally adopted its BESR performance standard in August of 1999, the standard reference wood bat was a high performance professional grade wood bat which produced an exit speed of 97-mph on the Baum Hitting Machine.

The speed with which a baseball leaves the bat (the Batted-Ball Speed) depends on three factors: the pitched-ball speed v_{ball} , the bat-swing speed v_{bat} , and the Ball-Exit-Speed-Ratio (BESR) which represents the effectiveness of the collision between bat and ball. The Batted-Ball Speed may be easily calculated from:^[2,3]

$$\text{BBS} = (\text{BESR} - 0.5) v_{\text{ball}} + (\text{BESR} + 0.5) v_{\text{bat}}$$

The 34-inch long wood baseball bat whose BESR value set the standard against which all other bats are compared was a high quality professional grade wood bat. This high performance wood bat was measured to have a Ball-Exit-Speed-Ratio of 0.728. When swung with a speed of 66-mph at a ball pitched at 70-mph this reference wood bat hits balls with a batted-ball speed of 97-mph.

NCAA 34" wood bat			
BESR	vball	vbat	BBS
0.728	70	66	97
0.728	70	76	108
0.728	95	80	113
Brown Univ. 34" wood bat			
BESR	vball	vbat	BBS
0.702	57	67	94
0.702	70	66	94
0.702	70	76	104

This 97-mph batted-ball speed does not, however, represent the maximum speed that this wood bat can hit a baseball. If a stronger player was able to swing the same bat with a bat-swing speed of 76-mph at a 70-mph pitched ball, the batted-ball speed would increase to about 108-mph*. And, if a major league player swung this same wood bat with a typical bat-swing speed of 80-mph towards a 95-mph fastball, the batted-ball speed could easily be as high as 113-mph. In fact, in order for a ball to just barely clear the wall for a

homerun in most major league ballparks, a baseball must leave the bat with a minimum speed of at least 110-mph, and this happens with considerably regularity. So, wood bats can hit balls with excessively high speeds.

However, not all wood bats are of the same quality as the NCAA professional grade reference wood bat. In fact, one frequently repeated complaint of minor league professional baseball players is a difficulty obtaining good quality wood bats. A large number of modern MLB players use maple bats instead of ash, while most players in the Babe Ruth era used heavy hickory bats. Maple and hickory are harder woods than ash, and the greater strength means that maple and hickory bats don't break as often as ash bats do. But, maple and hickory bats tend to be heavier and most players prefer lighter weight bats because a lighter bat can be swung with greater control. Recent problems with the emerald ash borer beetle are threatening the availability of quality ash for baseball bats, and the availability of good ash for baseball bats may be a serious concern in the near future. Bat manufacturers reserve the highest quality wood for professional players, with lesser quality wood used for minor leagues and wood only college leagues, and even lesser quality wood for youth bats, like the ones you can buy at your local sportings goods store. Differences in the quality of wood translate into differences in performance.

For example, the wood bat used in the Brown University field study^[4-6] has a BESR value of 0.702, which is significantly lower than the 0.728 value for the NCAA reference bat. The calculated BBS for this wood bat, assuming a bat-swing speed of 66-mph and a pitched-ball speed of 70-mph, is 94-mph, which is 3-mph slower than the NCAA reference bat. For the Brown University field study, pitched-ball speeds ranged from 48-mph to 66-mph with the average pitched-ball speed being 57-mph. Measured bat-swing speeds ranged from 60-mph to 75-mph with the mean bat-swing speed being 67-mph. As shown in the table above, a swing speed of 67-mph and ball speed of 57-mph results in a batted-ball speed of 94-mph, which agrees well with the experimental data from the field study. Stronger players who could swing this bat 10-mph faster could achieve batted-ball speeds around 104-mph. The data from the Brown University study shows that 3% of the balls hit from this lower quality wood bat had batted-ball speeds in excess of 100-mph.^[4] In the hands of a major league player swinging with a bat-speed of 80-mph towards a 95-mph fastball, this lower quality wood bat could easily hit a ball at 109-mph, which is 12-mph faster than the 97-mph associated with the BESR standard reference wood bat, and 16-mph faster than the assumed maximum speed of 93-mph for typical wood bats. An Australian field study^[7] also found that players swinging a commercially available wood bat were able to produce batted-ball speeds in excess of 110-mph. So, wood bats can hit balls at rather high speeds (well in excess of 93-mph), even if the wood bat is made from lesser quality wood than is used to make bats for professional players.

*There is a subtlety involved in the calculation of BBS, namely that the BESR depends on the Bat-Ball-Coefficient-Of-Restitution (BBCOR) which in turn depends on the relative speed between bat and ball. The faster the speed, the lower the BBCOR. So, calculating the BBS for higher v_{ball} and v_{bat} is not as simple as just plugging in a new speed and using the same BESR. The BESR decreases as the relative speed between bat and ball increases.

How much faster can a metal baseball hit a ball compared to a wood bat?

To answer this question I must limit the discussion to adult baseball bats approved for play by the NCAA for college baseball since 2000 or by the NFHS for high school baseball since 2003. It is true that metal baseball bats manufactured prior to 1999 were capable of hitting balls with excessively high speeds - I've read statements that particular late-1990's models were measured as hitting balls with

speeds of 120-130 mph, and I have no trouble believing this. I've measured the trampoline effect for some of these older bats and I'm not surprised that they can hit balls that fast. However, the metal bats that are currently used in college and high school play are not able to hit balls nearly as fast as their counterparts a decade ago. Since 1999 all bats approved for play by the NCAA and NFHS must pass a performance standard which requires:

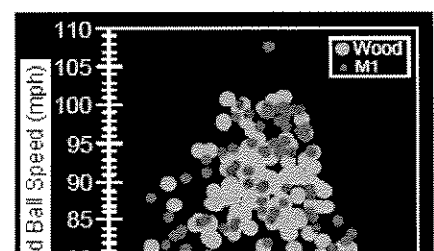
- the bat must have a BESR (Ball-Exit-Speed-Ratio) equal to or less than that of a wood bat of the same length
- the bat must have a MOI (moment-of-inertia) above a minimum value dependent on the bat length
- the numerical value of the bat weight (in ounces) must be no more than "3" units less than numerical value of the bat length (in inches). In other words, a 33-inch bat must weigh at least 30 ounces
- the maximum diameter of the bat barrel cannot exceed 2.625 inches

These requirements have significantly reduced the maximum performance of today's metal bats compared to metal bats from 10-15 years ago. In my article about the BESR Standard for NCAA Baseball I explain the physics behind the combined BESR and MOI standard, and what it means with regarding bat performance. The bottom line is that a modern, high performance legal metal bat might be able to hit balls about 5-mph faster than a professional quality wood bat of the same length.

There are several performance advantages that metal bats have over wood, but none of these advantages mean that metal bats hit balls with dangerously high speeds. I discuss the advantages of metal bats in detail in my article comparing metal and wood bats, but I'll quickly summarize the facts here.

1. Because a metal bat has a lower MOI (moment-of-inertia) it can be swung with greater speed and greater control. This means that a player using metal bat might be able to put the ball into play more often. This advantage is evidenced in the fact that batting averages are higher for college players when swinging metal bats compared to wood.
2. Metal bats don't break at the handle for inside pitches like wood bats do. An inside pitch that would jam a batter using a wood bat resulting in a broken-bat blooper for an out would likely be hit past the infield for a base hit by a player using a metal bat.
3. A metal bat is more forgiving for impacts outside of the "sweet spot" region on the barrel. Because of the barrel of a metal bat is hollow, there is a wider range of locations on the barrel of a metal bat where the batted-ball speed is close to the maximum value.
4. Hollow metal bats have a trampoline effect.^[8] The elastic properties of the hollow barrel improve the effectiveness of the bat-ball collision, and this the primary reason that it is possible for a metal bat to hit balls faster than a wood bat. The BESR performance standard places an upper limit on how effective the trampoline effect for a metal bat can be.

A metal bat will allow a player to put the ball into play more often, and will allow a player to hit a greater percentage of balls with higher batted-ball speeds. But, the current performance standards used to regulate adult baseball bats for college and high school allow a legal metal bat to exceed the performance of a high quality professional grade wood bat by only 5-mph. Of course, In the previous section I demonstrated that there could be as much as a 3 to 4-mph difference between the performance of a typical wood bat and the major league professional quality wood bat used to set the BESR standard. This suggests that the difference between a high performance legal metal bat and a low quality wood bat could be as much as 8-9 mph. But, it



is also true that not all metal bats will hit balls with the highest possible speeds. Just as wood bats don't all hit balls with the same speeds, there are also differences in quality of metal bats, and even for high performance metal bats, the majority of batted-ball speeds are well below the maximum speed. For example, the scatter plot at right shows the data collected for the wood bat (orange data points) and one of the metal bats (red data points) in the 1997 Brown University field study.^[5] This metal bat has a BESR value that is higher than the wood bat, and the average batted-ball speed for all impacts was more than 3-mph faster than the average for the wood bat. 21% of the balls hit by this metal bat had batted-ball speeds greater than 95-mph compared to only 9% of balls hit by the wood bat, evidence of advantage #3 above that more of the balls hit by the metal bat have speeds near the maximum value. However, 50% of the balls hit from this metal bat had batted-ball speeds of 89-mph or less, and with one single exception, the maximum batted-ball speed for this metal bat was actually lower than that of the wood bat. This is an example of a metal bat which "performs better" than wood, but doesn't actually hit balls any faster than wood.

How Quickly Will a Ball Hit by a Metal or Wood Bat Arrive at the Pitcher?

What does a 5-mph or 10-mph difference in batted-ball speeds mean concerning the ability of a pitcher to avoid being hit and injured? The scientific term that this question addresses is the **Available Pitcher Reaction Time (APRT)**. Simply stated the APRT represents the time it takes the ball to arrive at the pitcher's mound after leaving the bat. It depends on the initial speed with which the ball is hit, and the effects of air resistance during the flight, as well as the initial height above ground and the launch angle. In the 1998 NCAA memorandum^[1], it is stated that a ball traveling at 93-mph takes 0.4 seconds to travel 54 feet - but this result is incorrect because it does not account for air resistance. For my calculations I have assumed that the ball leaves the bat at a height of 31.5 inches above home plate and is initially traveling at an angle of 5° above the horizontal - in other words, a line drive starting just below waist level and aiming right for the pitcher's face. I am assuming that the ball must travel a distance of 54 feet before striking the pitcher. Quite often, the quoted arrival times neglect air resistance which is a big mistake. I accounted for air resistance using the drag coefficient data from Adair's book^[9] and the computational technique by Giordano^[10]. However, I did not account for variations in the density of air as a function of height above sea level, and I ignored any spin effects of the ball.

BBS	APRT
93 mph	0.416 s
97 mph	0.398 s
102 mph	0.378 s
107 mph	0.360 s
112 mph	0.343 s
117 mph	0.328 s
123 mph	0.312 s

The table at left compares the available pitcher reaction times (the time for the ball to travel 54 feet from the bat to the pitcher) for a range of batted-ball speeds. The calculations show that a ball leaving a bat at 97-mph, corresponding to the professional quality wood bat used to set the NCAA standard, will arrive at the pitcher's mound in just under 4-tenths of a second, while a ball hit from the highest performing metal bat currently allowed by NCAA rules would arrive two-hundredths of a second sooner (0.02s). And the difference in arrival times

corresponding to a 10-mph difference in batted-ball speeds is only 0.038 seconds. To help provide a

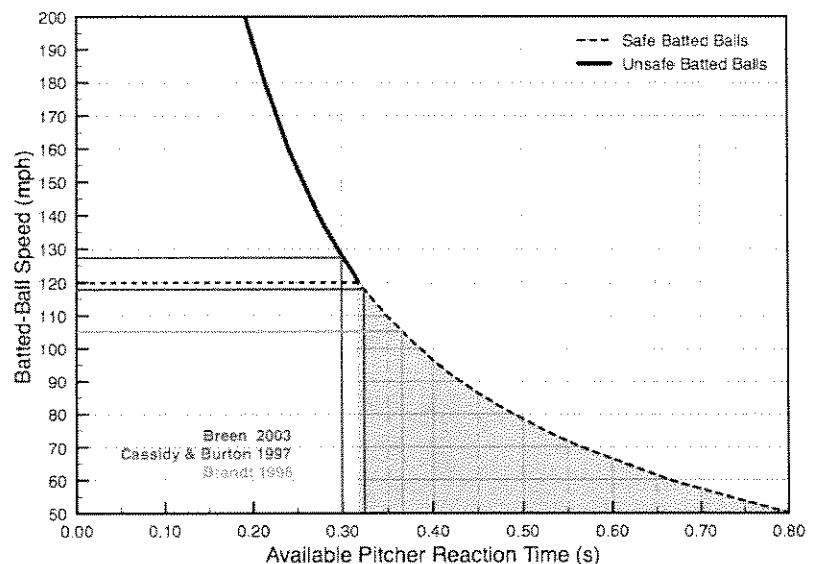
perspective for the 0.020s difference in arrival times for balls hit with metal and wood bats, consider that it takes 0.095s to blink an eye^[11]. In other words, the difference in arrival times between a ball hit by a wood bat and a ball hit by a high performance NCAA approved metal bat is only one-fifth of the time required to blink an eye! And the difference in the arrival times associated with a 10-mph faster batted-ball speed is less than half of the time required to blink an eye.

I find it very hard to believe having an extra 0.020s to react to a line drive would make any difference in whether or not a pitcher would be able to protect himself. When we look at the actual physical reaction times of players below, I think the inescapable conclusion must be that banning metal bats will not necessarily enable pitchers to avoid being hit by line drives hit directly towards them. The difference in arrival times corresponding to a 5-mph difference in batted-ball speeds is just not large enough to justify a claim that restricting players to using wood bats would make the game safer based on the argument that using wood bats would allow players sufficiently more time to react to a hit ball.

How Much Time does a Pitcher Need to React to Ball Hit Directly Towards Him?

This is the all important question. Unfortunately the topic of pitcher reaction time does not seem to be something that has been extensively studied and published in the research literature. I am aware of only one field study of reaction times published in a peer-reviewed journal and it deals with reaction times for children ages 9-16 with distances and ball speeds appropriate for Little League baseball^[12] instead of high school or college baseball. I am aware of three field studies of reaction times for college pitchers, but none of them have gone through the peer-review process and been published. The graphic at right compares the available pitcher reaction time (ball arrival time) as a function of batted ball speed (blue curve) and the measured reaction times for college pitchers from the three unpublished studies.

In 1989 P.E. Cassidy and A.W. Burton at the University of Minnesota investigated the response times of college baseball pitchers and infielders in an unpublished dissertation^[13] I haven't yet been able to obtain a copy of this dissertation to read it myself, but Dr. Trey Crisco summarized their conclusions in his report to the NCAA^[14]. Cassidy and Burton apparently surveyed the available literature on human reaction times in sports activities, and concluded that an average college baseball player is able to begin an accurate response to a batted ball within 0.125s of the ball being hit, and can complete a reasonable movement to catch, deflect or avoid the ball in an additional 0.200s. The total reaction time for a college player, according to Cassidy and Burton, is about 0.325 seconds.



In 1998 Dr. Richard Brandt, a physics professor at New York University, conducted an experimental study of physical reaction times for college baseball players.^[15] A total of 320 balls were fired from a

pitching machine at speeds between 85 and 105 mph towards 8 different college pitchers. The subjects were standing behind a protective screen at distances 20, 30, 40, and 50 feet from the pitching machine. Subjects were not able to determine the direction at which the ball was being aimed, and the subjects were tested to see whether or not they could successfully deflect a ball being fired towards them (the protective screen prevented the subjects from being injured). Dr. Brandt found that for college baseball players, a minimum of 0.368 seconds was sufficient to successfully deflect an approaching ball. Dr. Brandt's results suggest that a college pitcher should have sufficient time to avoid being hit at 97-mph by a ball hit from a wood bat, ball hit at 102-mph from a legal high performance metal bat, and even a ball hit by a wood or metal bat with a batted-ball speed of 110-mph.

In 2003 Kevin Breen conducted an unpublished study of potential response time of college baseball pitchers to balls hit in their direction.^[16] This study used actual pitchers and batters. The pitcher threw the ball and then had to react from his follow-through position and attempt to deflect the ball batted back directly towards him. Breen's study found that the average response time (the time between the ball was hit and the pitcher first began to move in response to seeing the ball) was 0.176s. When this response time was added to the time the pitcher took to move his body to avoid or deflect the batted ball, he found that every pitcher in his study was able to successfully avoid or deflect a batted ball within 0.300 seconds. This corresponds roughly to a batted-ball speed of 123-mph. Breen estimated that a 5-7 mph difference in batted ball speed would amount to a difference in arrival times of 0.015-0.023s which he concluded is far too short a period of time to make any difference as to whether or not a pitcher could avoid being hit by a batted ball. Mr. Breen's study suggests that college pitchers have enough time to react to balls hit by both wood and metal bats at speeds typical of the college game.

A very interesting observation from Mr. Breen's study is his conclusion that . . .

. . .the largest determining factor in whether a pitcher will be struck by a batted ball is whether the pitcher puts himself in a position to field the ball after delivery. Pitchers are coached to finish their follow through in a way that allows them to be in a position to field any ball that might be hit their way. If a pitcher fails to pitch in a manner so as to be prepared to field, there is a risk that the pitcher will be hit regardless of whether the ball is struck by an aluminum or wood bat. This is because a pitcher who improperly positions himself upon throwing a pitch can easily add well over 0.1 seconds to his reaction time.

If we summarize the results of these three studies we find that a college pitcher should be able to react and either deflect or avoid a ball hit at 120-mph, and would certainly be able to avoid being struck by a ball hit at 110-mph. Thus, a college pitcher should be able to react to the majority of balls hit by both wood and metal bats. However, if the pitcher is out of position so that he is not ready to field a ball hit directly towards him, he might not have enough time to avoid being struck by balls hit by wood or metal bats at speeds as low as 90-mph.

How does the speed of the ball at impact affect the severity of injury?

BBS	Arrival Time	Arrival Speed	Arrival Height
92 mph	0.421s	84 mph	4.5 ft
97 mph	0.398s	89 mph	4.8 ft
102 mph	0.378s	94 mph	5.1 ft
107 mph	0.360s	99 mph	5.3 ft

What I do find of interesting with regards to the discussion of injury risk are the speed with which the ball is still traveling and the height above ground when the ball reaches the position of the pitcher. These are results that I have not yet seen discussed at all in any

arguments regarding pitcher safety, but they seem to me to be of considerable potential importance in determining the potential severity of injury to a player who is struck by a ball. While the difference in arrival times may not be enough to make a difference in whether or not a pitcher can avoid being hit, the speed with which the ball impacts the pitcher and the location of the impact could affect the severity of an impact injury. My calculations show that an increase of 5-mph in the batted-ball speed means that the ball will also be traveling about 5-mph faster upon impact. In addition, the faster ball will also strike the pitcher about 4 inches higher on his body.

There is published research on the severity of injury for baseball impacts indicating that "the severity and frequency of injury increases as impact velocities increase."^[14] Additional research indicates that lowering the compression of the balls being used can reduce the severity of injury by a greater degree than lowering the batted-ball speed.^[17-18] This suggests that an organization or group truly concerned about safety and the risk of injury to pitchers and infielders might be better off arguing for the use of lower compression balls instead of attempting to ban metal bats. Both wood and metal bats are capable of hitting balls at high speeds, speeds which could cause serious injury upon impact. Using a lower compression ball would significantly reduce the potential severity of an injury, even if the ball was travelling at a high speed after being hit by a wood or metal bat.

Conclusion: Answering the Questions

1. **How fast can a ball be hit using a wood bat?** The batted-ball speed from a wood bat depends on the quality of the bat as well as on the pitched-ball speed and the bat-swing speed. Field studies have shown that measured batted-ball speeds for typical wood bats range from 70-mph to 110-mph. A high performance MLB quality wood bat in the hands of a good hitter could easily produce batted-ball speeds in excess of 115-mph.
2. **How much faster can a ball be hit with a metal bat compared to wood?** Just as was the case for wood, the batted-ball speed from a metal bat depends on the quality of the metal bat. High performance metal baseball bats that pass the current NCAA BESR and MOI performance standards might be able to hit balls about 5-mph faster than a high quality wood bat of the same length. Field studies have shown that extremely high performing metal bats can hit balls with speeds ranging from 70-mph to 110-mph, with some metal bats having a maximum batted-ball speed faster than wood and others having a maximum batted-ball speed about the same as wood. One advantage of using a metal bat is that a greater percentage of hits from a metal bat will have close to the maximum batted-ball speed, compared to a wood bat.
3. **How quickly would a ball hit by a wood or metal bat arrive at the pitcher?** A ball leaving the bat with a speed of 97-mph will travel the 54-feet to the pitcher in about 0.4 seconds. A ball leaving the bat 5-mph faster will arrive at the pitcher about 0.02s sooner, and a ball leaving the bat 10-mph will arrive at the pitcher about 0.04s sooner.
4. **How much time does a pitcher need to safely react to a batted ball?** Three unpublished field studies of reaction times for college pitchers concluded that a pitcher needs between 0.3 and 0.365 seconds to react to a ball hit directly towards him. According to the most realistic field study, pitchers should be able to deflect or avoid being struck by a ball leaving the bat at speeds of up to 120-mph. However, a pitcher who is out of position after his follow-through would need an additional 0.1 seconds and might not be able to avoid being hit by balls leaving the bat faster than 90-mph.
5. **How does the speed of the ball affect the severity of a ball-impact injury?** A ball leaving a wood or metal bat 5-mph faster will still be travelling 5-mph faster when it hits arrives at the pitcher, and the impact will be a couple of inches higher on the pitcher's body. Studies have shown

that the severity of injury increases with the impact speed of the ball. This suggests that impacts from balls hit by both wood and metal bats could cause severe injuries to a player who is unable to avoid being hit. This conclusion is validated by documented cases of players being killed by balls hit from both wood and metal bats.

My ultimate conclusion as a scientist, after investigating these questions, is that metal baseball bats currently legal for play under NCAA and NFHS regulations do not pose a safety risk that is significantly greater than the risk of playing baseball with wood bats. Injury statistics over the last 30 years indicate that baseball is one of the safest team sports played by high school and college players. Severe injuries resulting from pitchers being struck by batted balls, are tragic, but are extremely rare. The available scientific evidence suggests that banning metal bats will not necessarily make the game of baseball any safer.

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